

(19)



Europäisches Patentamt
European Patent Office
Office européen des brevets

(11)

EP 1 092 123 A1

(43) Date of publication:
18.04.2001 Bulletin 2001/16

(21) Application number: 99932020.3

(22) Date of filing: 29.06.1999

(51) Int. Cl. 7 : **G01B 9/02**

(86) International application number:
PCT/US99/14659

(87) International publication number:
WO 00/00782 (06.01.2000 Gazette 2000/01)

(84) Designated Contracting States:
BE DE DK ES FR GB GR IT NL PT SE

(30) Priority: 30.06.1998 US 91229 P

(71) Applicant: Lockheed Martin Corporation
Fort Worth, Texas 76108 (US)

(72) Inventor: **DRAKE, Thomas, E., Jr.**
Fort Worth, TX 76110 (US)

(74) Representative:
Fiener, Josef
Maximilianstrasse 57,
P.O. Box 12 49
87712 Mindelheim (DE)

(54) METHOD AND APPARATUS FOR DETECTING ULTRASONIC SURFACE DISPLACEMENTS USING POST-COLLECTION OPTICAL AMPLIFICATION

(87) This international application for which the EPO is a designated office has not been republished by the EPO according to article 158(1) EPC.

Cette demande internationale pour laquelle l'OEB est office désigné n'a pas été republiée par l'OEB en vertu de l'article 158(1) CBE.

Diese internationale Anmeldung, für die das EPA Bestimmungsamt ist, würde, gemäß Artikel 158(1) EPÜ, vom EPA nicht wieder veröffentlicht.

EP 1 092 123 A1



INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification: G01B 9/02	A1	(11) International Publication Number: WO 00/00782 (43) International Publication Date: 06 January 2000 (06.01.2000)
---	-----------	--

(21) International Application Number: PCT/US99/14659

(22) International Filing Date: 29 June 1999 (29.06.1999)

(30) Priority Data:
60/091,229 30 June 1998 (30.06.1998) US(60) Parent Application or Grant
LOCKHEED FORT WORTH COMPANY [/]; O. DRAKE,
Thomas, E., Jr. [/]; O. HULSEY, William, N., III ; O.**Published**(54) Title: **METHOD AND APPARATUS FOR DETECTING ULTRASONIC SURFACE DISPLACEMENTS USING POST-COLLECTION OPTICAL AMPLIFICATION**(54) Titre: **TECHNIQUE ET APPAREIL PERMETTANT DE DETECTER DES DEPLACEMENTS SUPERSONIQUES DE SURFACE PAR AMPLIFICATION OPTIQUE POST-DETECTION**

(57) Abstract

The present invention (300) detecting ultrasonic displacements includes a detection laser (320) to generate a first pulsed laser beam (325) to detect the ultrasonic surface displacements on a surface of the target (110). Collection optics (330) to collect phase modulated light from the first pulsed laser beam (325) either reflected or scattered by the target (110). An optical amplifier which amplifies the phase modulated light collected by the collection optics. An interferometer (150) which processes the phase modulated light and generates at least one output signal.

(57) Abrégé

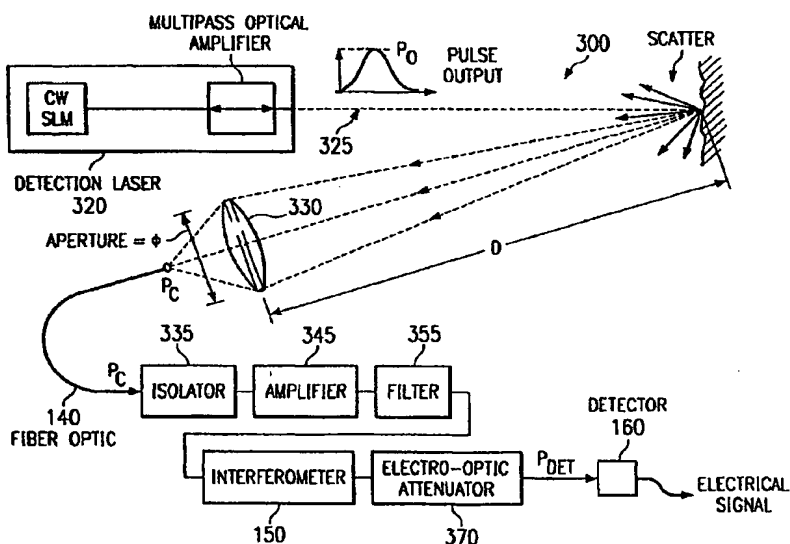
La présente invention (300) permet de détecter des déplacements ultrasoniques au moyen d'un laser de détection (320) qui produit un premier faisceau laser pulsé (325) destiné à détecter des déplacements superficiels ultrasoniques sur la surface d'une cible (110). Une optique collectrice (330) recueille le rayonnement lumineux à modulation de phase à partir du premier rayon laser pulsé (325) qui est soit réfléchi, soit diffusé par la cible (110). Un amplificateur optique amplifie le rayonnement à modulation de phase recueilli par l'optique collectrice. Un interféromètre (150) traite le rayonnement à modulation de phase et produit au moins un signal de sortie.

PCTWORLD INTELLECTUAL PROPERTY ORGANIZATION
International Bureau

INTERNATIONAL APPLICATION PUBLISHED UNDER THE PATENT COOPERATION TREATY (PCT)

(51) International Patent Classification ⁶ : G01B 9/02	A1	(11) International Publication Number: WO 00/00782 (43) International Publication Date: 6 January 2000 (06.01.00)
(21) International Application Number: PCT/US99/14659 (22) International Filing Date: 29 June 1999 (29.06.99) (30) Priority Data: 60/091,229 30 June 1998 (30.06.98) US (71) Applicant: LOCKHEED FORT WORTH COMPANY [US/US]; Building 200, 1 Lockheed Boulevard, Mail Zone 1237, Fort Worth, TX 76108 (US). (72) Inventor: DRAKE, Thomas, E., Jr.; 2418 5th Avenue, Fort Worth, TX 76110 (US). (74) Agent: HULSEY, William, N., III; Gray Cary Ware & Freidenrich LLP, Suite 1440, 100 Congress Avenue, Austin, TX 78701 (US).		(81) Designated States: CA, DE, GB, KR, SE, European patent (AT, BE, CH, CY, DE, DK, ES, FI, FR, GB, GR, IE, IT, LU, MC, NL, PT, SE). Published With international search report.

(54) Title: METHOD AND APPARATUS FOR DETECTING ULTRASONIC SURFACE DISPLACEMENTS USING POST-COLLECTION OPTICAL AMPLIFICATION



(57) Abstract

The present invention (300) detecting ultrasonic displacements includes a detection laser (320) to generate a first pulsed laser beam (325) to detect the ultrasonic surface displacements on a surface of the target (110). Collection optics (330) to collect phase modulated light from the first pulsed laser beam (325) either reflected or scattered by the target (110). An optical amplifier which amplifies the phase modulated light collected by the collection optics. An interferometer (150) which processes the phase modulated light and generates at least one output signal.

FOR THE PURPOSES OF INFORMATION ONLY

Codes used to identify States party to the PCT on the front pages of pamphlets publishing international applications under the PCT.

AL	Albania	ES	Spain	LS	Lesotho	SI	Slovenia
AM	Armenia	FI	Finland	LT	Lithuania	SK	Slovakia
AT	Austria	FR	France	LU	Luxembourg	SN	Senegal
AU	Australia	GA	Gabon	LV	Latvia	SZ	Swaziland
AZ	Azerbaijan	GB	United Kingdom	MC	Monaco	TD	Chad
BA	Bosnia and Herzegovina	GE	Georgia	MD	Republic of Moldova	TG	Togo
BB	Barbados	GH	Ghana	MG	Madagascar	TJ	Tajikistan
BE	Belgium	GN	Guinea	MK	The former Yugoslav Republic of Macedonia	TM	Turkmenistan
BF	Burkina Faso	GR	Greece	ML	Mali	TR	Turkey
BG	Bulgaria	HU	Hungary	MN	Mongolia	TT	Trinidad and Tobago
BJ	Benin	IE	Ireland	MR	Mauritania	UA	Ukraine
BR	Brazil	IL	Israel	MW	Malawi	UG	Uganda
BY	Belarus	IS	Iceland	MX	Mexico	US	United States of America
CA	Canada	IT	Italy	NE	Niger	UZ	Uzbekistan
CF	Central African Republic	JP	Japan	NL	Netherlands	VN	Viet Nam
CG	Congo	KE	Kenya	NO	Norway	YU	Yugoslavia
CH	Switzerland	KG	Kyrgyzstan	NZ	New Zealand	ZW	Zimbabwe
CI	Côte d'Ivoire	KP	Democratic People's Republic of Korea	PL	Poland		
CM	Cameroon	KR	Republic of Korea	PT	Portugal		
CN	China	KZ	Kazakhstan	RO	Romania		
CU	Cuba	LC	Saint Lucia	RU	Russian Federation		
CZ	Czech Republic	LI	Liechtenstein	SD	Sudan		
DE	Germany	LK	Sri Lanka	SE	Sweden		
DK	Denmark	LR	Liberia	SG	Singapore		
EE	Estonia						

Description

5

10

15

20

25

30

35

40

45

50

55

METHOD AND APPARATUS FOR DETECTING
ULTRASONIC SURFACE DISPLACEMENTS USING
POST-COLLECTION OPTICAL AMPLIFICATION

RELATED APPLICATIONS

This application claims the benefit of U.S. Provisional Application No. 60/091,229 filed on June 30, 1998. Additionally, this application incorporates by reference the prior U.S. Provisional Application No. 60/091,240 filed on June 30, 1998 entitled "METHOD AND APPARATUS FOR ULTRASONIC LASER TESTING" to Thomas E. Drake.

TECHNICAL FIELD OF THE INVENTION

The present invention relates generally to a system and method of non-destructive evaluation of materials, and more particularly, to a system and method of processing optical information to detect ultrasonic surface displacements through the use of at least one laser and optically amplifying the scattered return of laser light after collecting it to perform a non-destructive evaluation of a material.

BACKGROUND OF THE INVENTION

In recent years, the use of advanced composite structures has experienced tremendous growth in the aerospace, automotive, and many other commercial industries. While composite materials offer significant improvements in performance, they require strict quality control procedures in the manufacturing processes. Specifically, non-destructive evaluation ("NDE") methods are required to assess the structural integrity of composite structures, for example, to detect inclusions, de-laminations and porosities. Conventional NDE methods are very slow, labor-intensive, and costly. As a result, testing procedures adversely increase the manufacturing costs associated with composite structures.

Various systems and techniques have been proposed to assess the structural integrity of composite structures. One method to generate and detect ultrasound using lasers discloses the use of a first modulated, pulsed laser beam for generating ultrasound on a work piece and a second pulsed laser beam for detecting the ultrasound. Phase modulated light from the second laser beam is then demodulated to obtain a signal representative of the ultrasonic motion at the surface of the work piece. A disadvantage of such a system has been that in order to improve the systems ability to detect ultrasonic motion at the surface of the work piece a more powerful laser is required which may be impractical to construct or could damage the workpiece due to excessive heating.

Another method to generate and detect ultrasound using lasers is disclosed in U.S. Patent Application Serial

5
10 No. 60/091,240 filed on June 30, 1998 to T.E. Drake
entitled "Method And Apparatus For Ultrasonic Laser
Testing" hereafter *DRAKE*. *DRAKE* discloses the use of a
15 first modulated, pulsed laser beam for generating
ultrasound on a work piece and a second pulsed laser beam
for detecting the ultrasound. Phase modulated light from
the second laser beam is then demodulated to obtain a
20 signal representative of the ultrasonic motion at the
surface of the work piece. A disadvantage of such a system
10 has been that in order to improve the systems ability to
detect ultrasonic motion at the surface of the work piece a
25 more powerful laser is required which suffers from the same
problems as the '166 patent.

30 Another method to generate and detect ultrasound using
lasers discloses the use of a laser to detect deformations
15 of a oscillatory or transient nature on a remote target
surface. The deformations on the remote target surface can
be produced by an ultrasound wave or other excitation.
35 Light from the laser is scattered by the deformations, some
of which light is collected by collecting optics and
20 transmitted via a fiber optic to a beam splitter which
deflects a small portion of the collected light to a
reference detector and delivers the remaining portion of
40 the light to a confocal Fabry-Perot interferometer, which
generates an output signal indicative of the deformations
25 on the remote target surface. The reference detector
measures the intensity of the scattered laser light at the
input of the interferometer to generate a reference signal.
50 A stabilization detector measures the intensity of the
30 scattered laser light at the output of the interferometer

5

4

10

15

20

10

25

30

35

20

40

45

50

30

55

to generate a prestabilization signal. The ratio of the reference signal to the prestabilization signal is used to generate a final stabilization signal which drives a piezoelectric pusher inside the interferometer to adjust its resonant frequency. A disadvantage of such a system has been that a portion of the signal is lost at the beam splitter when sent to the reference detector. Again in order to improve the systems ability to detect ultrasonic motion at the surface of the work piece a more powerful laser is required.

An alternative to using a more powerful laser is to decrease the working distance to the part and/or increase the size of the collection aperture. This reduces the F-number of the optical system and has the disadvantage of a corresponding reduction in the working depth of field (DOF). DOF is a measure of how far away from the ideal focal plane an object can be and still maintain acceptable performance. Lower F-number designs generally result in a smaller scan area capability and often require active focusing lens assemblies in order to maintain efficient light collection while scanning complex shaped components. Large collection apertures require the use of single-mirror optical scanning systems, usually in a two-axis gimbal configuration, that are cumbersome and generally slow.

A need exists for a ultrasonic laser system which improves detection capabilities of the system to detect ultrasonic motion at the surface of the workpiece without damaging the workpiece.

Moreover, there is a need for an ultrasonic laser system which improves detection capabilities of the system

5

5

10

to detect ultrasonic motion at the surface of the workpiece
using practical lasers without damaging the workpiece and
functioning with sufficiently large DOF.

15

20

25

30

35

40

45

50

55

5

6

10

SUMMARY OF THE INVENTION

15

5

The present invention provides a system and method for detecting ultrasonic surface displacements on a remote target that substantially eliminates or reduces disadvantages and problems associated with previously developed laser ultrasonic systems and methods.

20

10

25

30

15

More specifically, the present invention provides a system and method for detecting ultrasonic surface displacements on a target. The system for detecting ultrasonic surface displacements on a target includes a detection laser to generate a first pulsed laser beam to detect the ultrasonic surface displacements at the remote target. Collection optics collect the phase modulated light from the first pulsed laser beam scattered by the remote target. Scattering of the laser beam by the remote target includes all reactions between laser beam and the remote target where the laser beam is redirected with phase modulations induced by surface vibrations or perturbations such as those produced by ultrasonic mechanisms. An optical amplifier amplifies the phase modulated light collected by the collection optics. This optical signal in turn is processed by an interferometer to generate an output signal. A processor or computer system processes the output signal from the interferometer to obtain data representative of the ultrasonic surface displacements at the remote target.

35

20

40

45

25

50

30

Another embodiment of the present invention includes a method for detecting ultrasonic surface displacements. This method includes the steps of first generating ultrasonic surface displacements at a remote target. These ultrasonic

55

5

7

10

15

5

displacements are scattered by a first pulsed laser beam creating a phase modulated scattered return. This phase modulated light from the first pulsed laser beam either reflected or scattered by the remote target is then collected and optically amplified. This optical signal is processed to obtain data representative of the ultrasonic surface displacements at the remote target.

20

10

25

30

15

A technical advantage of the present invention is that an improved method for ultrasonic laser testing is provided. That provides rapid, non-contact, and non-destructive inspection techniques that can be applied to complex composite structures. The present invention provides a flexible, accurate and cost effective method for inspecting complex composite structures that is able to rapidly scan and test large-sized composite structures.

35

20

Another technical advantage of the present invention is an improved signal-to-noise ratio for the test system due to increased detection intensities reducing the required intensity of the detection laser.

40

Another technical advantage of the present invention is the ability to use a detection laser with lower output power.

45

25

Another technical advantage of the present invention is the possibility of an increased working distance between the target object and the scanner by optically amplifying the phase modulated light.

50

55

BRIEF DESCRIPTION OF THE DRAWINGS

For a more complete understanding of the present invention and advantages thereof, reference is now made to the following descriptions taken in conjunction with the accompanying drawings in which like reference numbers indicate like features and wherein:

FIGURE 1 illustrates a known setup for detecting ultrasonic surface displacements using a detection laser beam;

FIGURE 2 is a typical gain plot for an optical amplifier illustrating Laser Output versus Number of Passes Through The Amplifier;

FIGURE 3 illustrates the use of a post-collection multipass optical amplifier to yield an improved signal-to-noise ratio;

FIGURE 4 illustrates the use of doped fiber optics and an optical pump for post-collection optical amplification;

FIGURE 5 illustrates a setup for testing the gain associated with post-collection optical amplification;

FIGURE 6 illustrates reflected and transmitted signals generated using the setup of FIGURE 5 without post-collection optical amplification; and

FIGURE 7 illustrates reflected and transmitted signals generated using the setup of FIGURE 5 with post-collection optical amplification.

DETAILED DESCRIPTION OF THE INVENTION

Preferred embodiments of the present invention and its advantages are understood by referring to FIGURES 1 through 7 of the drawings, like numerals being used for like and corresponding parts of the various drawings. The systems and methods of *DRAKE* are incorporated by reference in the present invention.

FIGURE 1 illustrates a known setup for generating and detecting ultrasonic surface displacements using a detection laser beam. Detection system 100 utilizes a detection laser 120 to detect ultrasonic surface displacements on a remote target. Detection laser 120 may incorporate a continuous wave (CW) single longitudinal-mode (SLM) seed laser along with a multipass optical amplifier to generate a laser beam 125 with a power P_0 . The ultrasonic surface displacements in the remote target 110 modulate, scatter and reflect detection laser beam 125, represented by the arrows directed away from the remote target 110. When detection laser beam 125 interacts with the ultrasonic waves present in the remote target 110, detection laser beam 125 is reflected as phase-modulated light. Specifically considering the electric field representation of an incident laser beam 125 as:

$$E_{in} = E \cdot e^{i(\omega t - kx)}$$

where E is the electric field amplitude, ω is the radial frequency, t is time, the wave vector is defined as $k = \frac{2\pi}{\lambda}$,

10

λ is the wavelength, and x is the distance traveled to the target. Beam 125 is scattered or reflected from a surface 110 experiencing a time dependent displacement $\Delta(t)$, and returns along the same path, producing a modulated electric field for $\Delta(t) \ll \lambda$ defined as:

$$E_{in} = E \cdot [1 - 2ik\Delta(t)]e^{i\omega t}$$

The $\Delta(t)$ term must be demodulated using interferometer 150 from this expression for reconstruction of the time history of the surface displacement. Some of the phase modulated light is captured by collection optics 130, which directs the phase-modulated light via fiber optic 140 into interferometer 150. Interferometer 150 demodulates the phase-modulated light and directs its outputs into detector 160 which generates an analog signal for processing.

Collection optics 130 has an aperture diameter of ϕ and is spaced a distance D from remote target 110. The power of the collected, phase-modulated light as measured at the output of the collector is P_c , and therefore, the power at the input of the interferometer is substantially P_c since there is very little transmission loss associated with fiber optic 140. A typical diffuse surface will have the following relationship describing the amount of collected light for a specified optic diameter and working distance:

$$P_c = \frac{P_o}{4} \left(\frac{\Phi}{D} \right)^2 (1 - A) \cos(\theta)$$

Where A represents the absorption of the target and θ is the angle of incidence. A perfect white diffuse target would have $A = 0$, and a typical dark composite might have an absorption of 90% ($A = 0.9$). Because the loss in interferometer 150 is minimal, the power of the input signal to the detector (P_{DET}) is substantially the same as P_c .

The signal-to-noise ratio of detector 160 is directly proportional to the square root of the input power:

$$SNR \propto \sqrt{P_{DET}}$$

The formula above suggests that the SNR can be improved by increasing P_o , or ϕ , or by decreasing D . Increasing the ratio of ϕ/D will decrease the depth of field of detection system 100, which is undesirable because a decreased depth of field is less flexible.

Alternatively, P_o can be increased. One approach to increase the output of detection laser 120 is to use a shorter pulse width. The pulse of detection laser beam 125, however, must be of a sufficient width to permit detection of ultrasonic surface displacements, and therefore, decreasing its pulse duration degrades its ability to detect such displacements. A second approach is to amplify the detection laser using a multiple pass optical amplifier. However, the gain of a conventional optical amplifier is dependent upon the power of the input signal.

FIGURE 2 illustrates a gain plot 200 for a typical optical amplifier as a function of the number of passes through the amplifier. Gain plot 200 shows that the typical

amplifier has a linear gain 210 for small input signals. However, the gain 220 is not linear as the input signal increases, as illustrated by the leveling of gain plot 200 as the amplifier approaches saturation. Gain plot 200 demonstrates that adding multiple amplifier sections quickly reaches a point of diminishing returns, and therefore, the ability to increase SNR by increasing P_o , is limited.

FIGURE 3 illustrates a setup for a new and improved detection system 300. Detection system 300 utilizes a detection laser 120 to detect ultrasonic surface displacements in a remote target 110. Detection laser 120 may incorporate a multi-pass optical amplifier to generate a laser beam 125 with a power P_o .

The ultrasonic surface displacements in a remote target 110 may be produced using a generation laser, a piezoelectric transducer, electrical discharge, projectile impact or other known means. The ultrasonic surface displacements modulate, scatter and reflect detection laser beam 325. When detection laser beam 325 interacts with the ultrasonic waves present at the remote target 110, detection laser beam 325 is reflected as phase-modulated light, as illustrated by the arrows directed away from remote target 110.

When a generation laser is used to induce ultrasonic surface displacements, the generation laser must be of a frequency that is readily absorbed into the remote target 110 without causing ablation or breaking down the remote target material, and it must be of sufficient pulse length to induce ultrasonic surface deformations. For example, a

5

13

10

transverse-excited atmospheric ("TEA") CO₂ laser can be used to produce a 10.6 micron wavelength beam for a 100

15

5

nanosecond pulse. The power of the laser must be sufficient to deliver, for example, a 0.5 joule pulse to the remote target, which may require a 50 watt laser. The generation laser should be absorbed as heat into the remote target thereby causing thermoelastic expansion without ablation.

20

10

Generally, utilizing a wavelength in the ultraviolet range is undesirable because such light can potentially damage the composite material. Optionally, the generation laser and the detection laser may also be applied coaxially to the surface of the remote target object.

25

30

15

The detection laser 320 must be of a frequency that does not induce ultrasonic surface displacements. For example, a Nd:YAG laser can be used. The power of this laser must be sufficient to deliver, for example, a 100 milli-joule, 100 μ second pulse, which may require a one kilo-watt laser.

35

40

20

When detection laser beam 325 interacts with the ultrasonic waves present in remote target 110, detection laser beam 325 is reflected as phase-modulated light. Some of the phase modulated light is captured by collection optics 330. Collection optics 330 may utilize either a large aperture collector or a small aperture collector. For example, a large aperture collector may be a Cassegrain-type reflector, comprised of a primary spherical reflective surface which focuses light upon a secondary spherical reflective surface, which in turn, collects the light. For increased speed and flexibility a small aperture collector is desirable.

45

25

50

30

55

Collection optics 330 collect the phase-modulated light and directs it into fiber optic carrier 140, which in turn, directs the phase-modulated light into optical amplifier 345. Optical amplifier 345 may be a multi-pass optical amplifier or other optical amplifier as known to those skilled in the art. Optical isolator assembly 355 will prevent reflected phase modulated light feedback into optical amplifier 345. The amplified, phase-modulated is directed through optical isolator assembly 355. The amplified, phase-modulated light is then directed into interferometer 150, wherein the light is demodulated. The demodulated light is then directed into detector 160 which generates an analog output signal.

This analog signal may comprise an optical signal which may be converted into a digital signal. This digital signal may then be processed to extract data representative of the ultrasonic displacements at the remote target.

Optionally, an optical ranging unit (not shown) can be integrated into detection system 300 to utilize a ranging laser beam to determine the distance between the remote target 110 and the scanning system. Often, it is important to know the distance by which remote target 110 is located from the scanner so that a topographical contour can be created for the remote target and can be correlated to the optical data being collected. Generally, this correlation is recorded on a point-by-point basis.

The power of the collected, phase-modulated light as measured at the output of the collector is P_c , and optical amplifier 345 has a gain G . Therefore, the power of the signal at the output of optical amplifier is $P_c * G$.

Because the interferometer has a low loss rate, the power at the output of the interferometer (i.e., the power at the input to the detector, P_{DET}) is substantially $P_c * G$.

The signal-to-noise ratio of detector 160 is directly proportional to the square root of the input power:

$$SNR \propto \sqrt{P_{DET}}$$

The introduction of the optical amplifier to amplify P_c , however, permits the SNR to be improved by increasing P_c , in addition to increasing P_o , or ϕ , or by decreasing D .

There are several added advantages. It is no longer critical to increase P_o to the maximum, and therefore, any amplifier that amplifies detection laser 320 can be operated in the efficient, linear gain region. Moreover, optical amplifier 345 can also be operated in the efficient, linear gain region. Because the need for high gain in any one of the amplifiers has been decreased, less costly amplifiers can be used in detection system 300. The increased performance associated with a two amplifier approach (one amplifier in detection laser 320, and one amplifier post-collection), will permit the system to use a smaller aperture ϕ and a greater distance D , therefore, providing detection system 300 with greater flexibility without any degradation in performance. On the contrary, detection system 300 enjoys increased performance.

Moreover, optical amplifier 345 will not contribute any substantial additional noise unless P_c exceeds 1 photon per bandwidth of the measurement. Thus, the post-collection optical amplification approach improves the SNR without any substantial increase in noise. Electrical amplification of the analog signal subsequent to detector 160 will not

improve the SNR above $\sqrt{P_c}$. This is so because both the signal and the noise component will be amplified.

The following examples illustrate embodiments of the present invention, but should not be viewed as limiting the scope of the invention.

EXAMPLE 1 (No Post-Collection Amplification)

$$P_o = 10^3 \text{ W Peak Power (100 mJ pulse, 100 } \mu\text{S)}$$

$$P_c = 10^{-5} * P_o$$

Though P_o is significant, P_c can be only a small fraction of P_o , because collection efficiency depends upon the reflectivity of remote target 110, and D. Given these assumptions,

$$P_{DET} = 10^{-5} * 10^3 \text{ W}$$

$$= 10^{-2} \text{ W}$$

$$= 10 \text{ mW}$$

EXAMPLE 2 (With Post-Collection Amplification)

$$P_o = 10 \text{ W Peak Power (1 mJ pulse, 100 } \mu\text{S)}$$

$$P_c = 10^{-5} * P_o$$

In Example 2, P_o is 1/100 of the power of the detection laser in Example 1 above. P_c is calculated using the same assumptions as in Example 1. A post-collection amplifier has a gain of 10^4 , which results in

$$P_{DET} = 10^4 * P_c$$

$$= 10^4 * 10^{-5} * P_o$$

$$= 10^4 * 10^{-5} * 10 \text{ W}$$

$$= 1 \text{ W}$$

Since SNR is proportional to $\sqrt{P_{DET}}$, the increase in SNR for Example 2 over Example 1 is the square root of the

increase in power delivered to the detector. That is, there is a 10-fold increase ($\sqrt{100}$) in the SNR for Example 2 over Example 1.

As these two examples illustrate, the use of post-collection optical amplification permits the use of a detection laser with 1/100 of the power as that without the post-collection optical amplifier, yet provides a 10-fold increase in SNR.

FIGURE 4 illustrates a second embodiment to achieve post-collection optical amplification. The setup illustrated in FIGURE 4 is very similar to that presented in FIGURE 3, and therefore, only the differences will be discussed here.

Collection optics 330 collect the phase-modulated light and direct it into a doped optical fiber 440, which in turn, directs the phase-modulated light into interferometer 150, wherein the light is demodulated. The demodulated light is then directed into detector 160 which generates an analog output signal. An optical pump 445 is coupled to doped fiber optic carrier 440, and acts as an amplifier to increase the power of the signal. The amplified, phase-modulated light is directed through optical isolator assembly 355 prior to being delivered to interferometer 150. The combination of doped optical fiber carrier 440 and optical pump 445 results in an effective gain of $e^{2\alpha L}$. A specific optical amplifier is not critical to the present invention, and therefore, other known optical amplifiers may be used.

FIGURE 5 illustrates a setup for testing the use of post-collection optical gain approach of the present

invention. Detection laser 520 generates a detection laser beam 525 which is directed upon a remote target 510 to detect ultrasonic surface displacements thereon. Detection laser beam 525 is amplified by two external amplifiers 521, 522 before being directed upon surface 510.

In this test setup, the ultrasonic surface displacements in remote target 510 are produced using a piezoelectric transducer 515, which transducer is synchronized using synchronizing means 570. The ultrasonic surface displacements modulate, scatter and reflect detection laser beam 525. When detection laser beam 525 interacts with the ultrasonic waves present in remote target 510, detection laser beam 525 is reflected as phase-modulated light from remote target 510. The reflected, phase-modulated light is collected and directed into optical amplifier 545 where it may be amplified if desired, or may be passed through without amplification, depending on whether amplifier 545 is active or inactive. From amplifier 545, the light is directed via fiber optic 540 into interferometer 550, wherein the reflected and transmitted components of the signal are detected using detectors 560A and 560B, respectively. Detectors 560A and 560B generate analog signals which are then captured for comparison by measurement device 580.

FIGURE 6 illustrates the reflected and transmitted signals as detected when amplifier 545 is inactive, and thus, passes the collected, phase-modulated light without amplification.

FIGURE 7 illustrates the reflected and transmitted signals as detected when amplifier 545 is active, and thus,

amplifies the collected, phase-modulated light. A comparison of the signals illustrated in FIGURES 6 and 7 demonstrates that the reflected and transmitted signals have been amplified significantly without any substantial increase in noise.

The present invention provides an improved method for ultrasonic laser testing this method provides rapid, non-contact, and non-destructive inspection techniques that can be applied to complex composite structures. This provides a flexible, accurate and cost effective method for inspecting complex composite structures that was not previously available. This method is able to rapidly scan and test large-sized composite structures

The present invention also improves the signal-to-noise ratio for a laser ultrasonic test system. This increased sensitivity is due to increased detection intensities thus reducing the required intensity of the detection laser.

Similarly, the present invention provides the ability to use a detection laser with lower output power. This allows the use of smaller collection optics and optical scanners.

Moreover, another technical advantage of the present invention is the possibility of an increased working distance between the target object and the scanner by optically amplifying the phase modulated light.

Although the present invention has been particularly shown and described in detail, it should be understood that various changes, substitutions and alterations can be made

5

20

10

hereto without departing from the spirit and scope of the
invention as defined in the appended claims.

15

20

25

30

35

40

45

50

55

Claims

5

10

15

20

25

30

35

40

45

50

55

WHAT IS CLAIMED IS:

1. A method for detecting ultrasonic surface displacements on a target, comprising the steps of:
generating ultrasonic surface displacements at the target;
using a first pulsed laser beam to detect the ultrasonic surface displacements at the target;
collecting phase modulated light from the first pulsed laser beam scattered by the target;
optically amplifying the phase modulated light after the phase modulated light has been collected;
preventing reflected phase modulated light feedback into an optical amplifier with at least one optical isolation assembly placed in the path of propagation of the phase modulated light which has been collected; and
processing the phase modulated light to obtain data representative of the ultrasonic surface displacements at the target.

2. The method of Claim 1 wherein the step of processing the phase modulated light further comprises the steps of:
using an interferometer to demodulate the phase modulated light for creating at least one optical signal;
converting the at least one optical signal into at least one digital signal; and
using a digital signal processor to process the at least one digital signal.

5
10
15
20
25
30
35
40
45
50
55

3. The method of Claim 2 wherein the step of converting the at least one optical signal into at least one digital signal further comprises the steps of:
converting the at least one optical signal into at least one analog signal; and
converting the at least one analog signal into at least one digital signal.

4. The method of Claim 1 wherein the ultrasonic surface displacements at the target are generated using a second pulsed laser beam and wherein the first pulsed laser beam is applied coaxially with the second pulsed laser beam.

5. The method of Claim 1 wherein the step of optically amplifying the phase modulated light is accomplished using a multi-pass optical amplifier.

6. The method of Claim 1 wherein the step of optically amplifying the phase modulated light is accomplished using a doped fiber optic carrier coupled to an optical pump.

7. The method of Claim 1 further comprising amplifying the first pulsed laser beam prior to applying it to the target.

5
10 8. A method for generating and detecting ultrasonic surface displacements on a target further comprising the steps of:

15 5 using a first pulsed laser beam to generate the ultrasonic surface displacements at the target;
amplifying a second pulsed laser beam;
20 directing the second pulsed laser beam at the target to detect the ultrasonic surface displacements;
collecting phase modulated light from the second
10 pulsed laser beam which is scattered by the target;
25 optically amplifying the phase modulated light after the phase modulated light has been collected;
preventing reflected phase modulated light
30 15 feedback into an optical amplifier with at least one optical isolation assembly placed in the path of propagation of the phase modulated light which has been collected; and
35 20 processing the phase modulated light to obtain data representative of the ultrasonic surface displacements at the target.

40 9. The method of claim 8, wherein the second pulsed laser beam is applied coaxially with the first pulsed laser beam.

45 25 10. The method of Claim 8 wherein the step of optically amplifying the phase modulated light is accomplished using a multi-pass optical amplifier.
50
55

5
10 11. The method of Claim 8 wherein the step of optically amplifying the phase modulated light is accomplished using a doped fiber optic carrier coupled to an optical pump.

15 5 12. The method of Claim 8 wherein the step of processing the phase modulated light comprises:

20 using an interferometer to demodulate the phase modulated light to create at least one optical signal;

10 converting the at least one optical signal into at least one digital signal; and

25 using a digital signal processor to process the at least one digital signal.

30 15 13. The method of Claim 12 wherein the step of converting the at least one optical signal into at least one digital signal comprises:

35 converting the at least one optical signal into at least one analog signal; and

20 converting the at least one analog signal into at least one digital signal.

40 14. The method of claim 8 further comprising
45 25 processing the data representative of the ultrasonic surface displacements to determining a location of flaws or an discontinuities at the target.

50

55

5

25

10

15. An system for detecting ultrasonic surface displacements occurring on a surface of a target comprising:

15

5

a detection laser to generate a first pulsed laser beam to detect the ultrasonic surface displacements at the target;

20

collection optics for collecting phase modulated light from the first pulsed laser beam scattered by the target;

10

an optical amplifier to amplify the phase modulated light collected by the collection optics;

25

at least one optical isolation assembly placed in the path of propagation of the phase modulated light collected by the collection optics for preventing reflected laser light feedback into optical amplifier;

30

15

an interferometer to process the phase modulated light and generate at least one output signal; and

35

a processing unit to process the at least one output signal to obtain data representative of the ultrasonic surface displacements at the target.

20

40

16. The system of Claim 15 further comprising an optical amplifier to amplify the first pulsed laser beam generated by the detection laser prior to directing the first pulsed laser beam upon the target.

45

25

50

17. The system of Claim 15 further comprising an optical ranging unit to calculate a distance by which the target is separated from the system.

30

55

5
10 18. The system of claim 15 further comprising a
generation laser to generate a second pulsed laser beam to
induce the ultrasonic surface fluctuations, and wherein the
15 second pulsed laser beam is applied coaxially with the
5 first pulsed laser beam.

20 19. The system of claim 15 wherein the optical
amplifier is a multi-pass optical amplifier.

10 20. The system of claim 15 wherein the optical
25 amplifier is comprised of a doped fiber optic carrier and a
optical pump coupled thereto.

1/4

FIG. 1
(PRIOR ART)

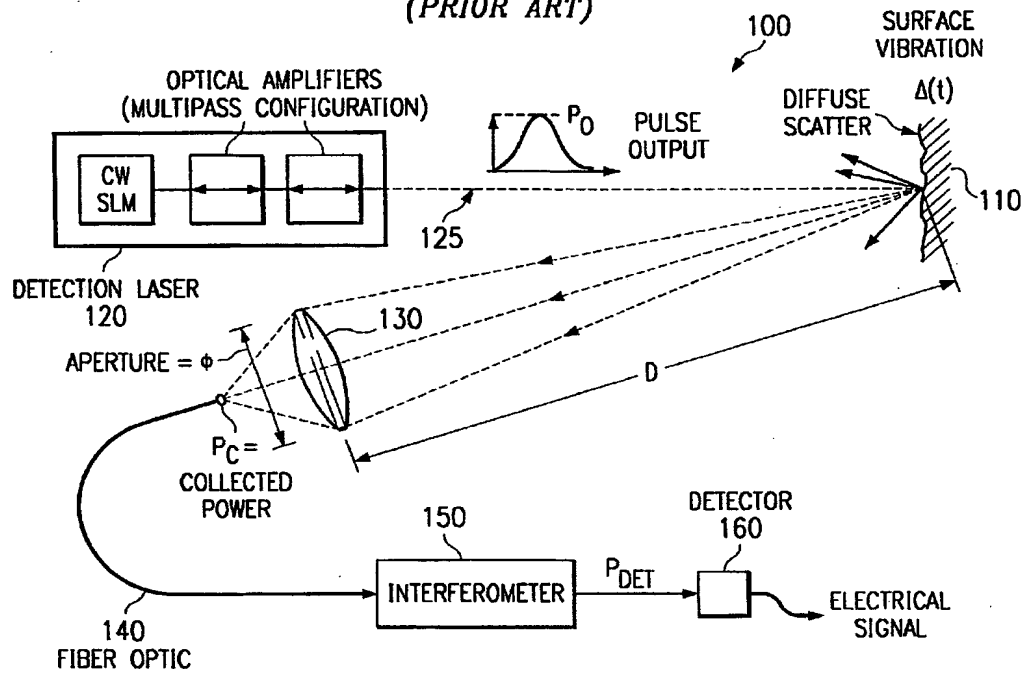
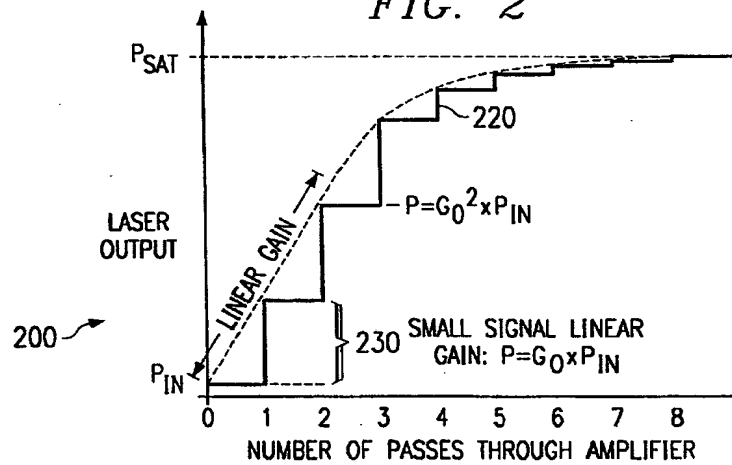
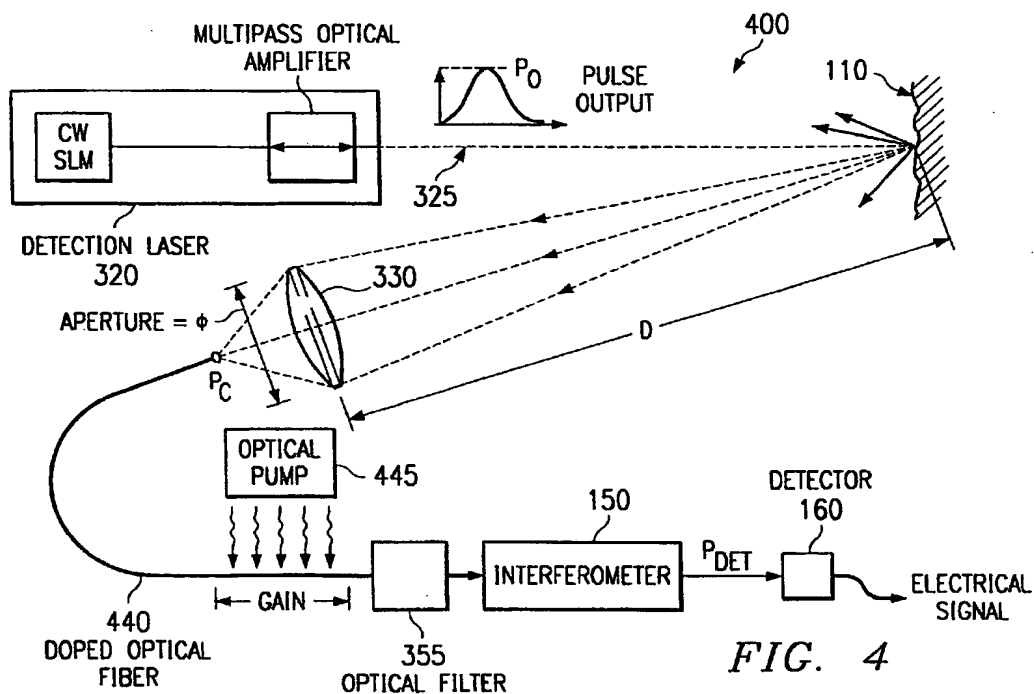
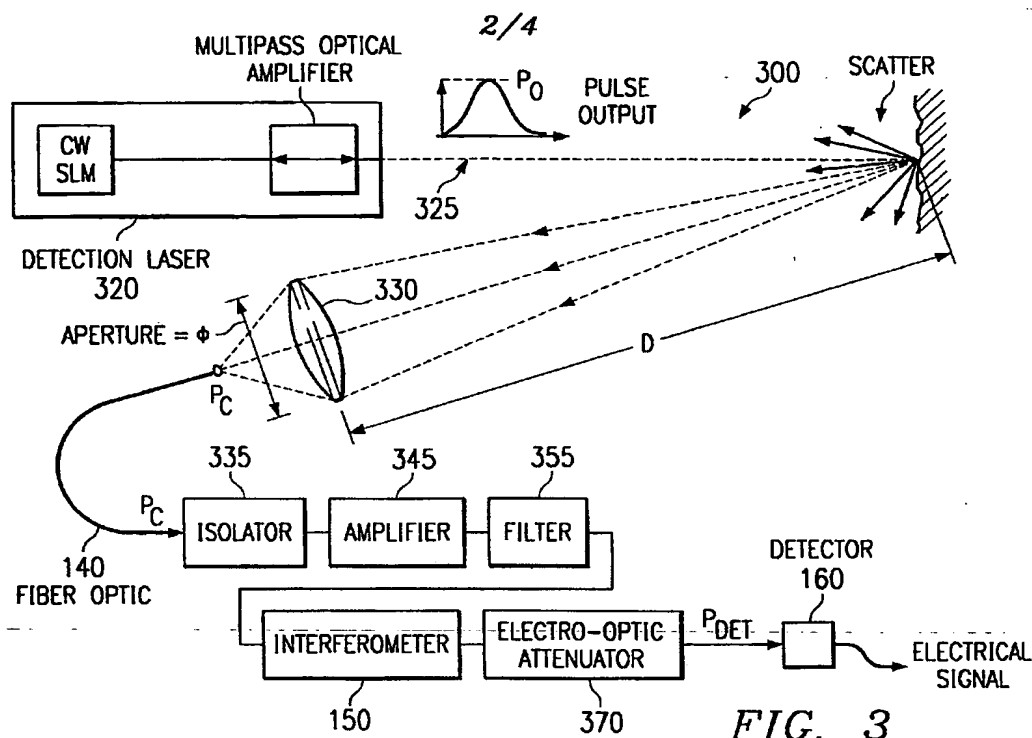


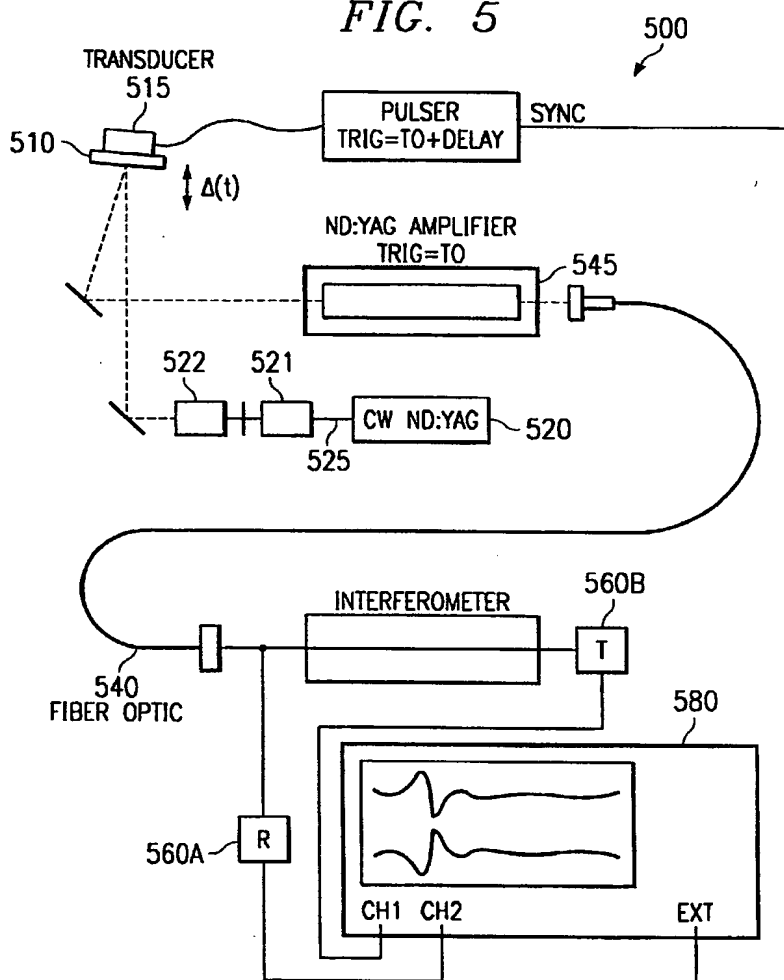
FIG. 2





3/4

FIG. 5



4/4

FIG. 6

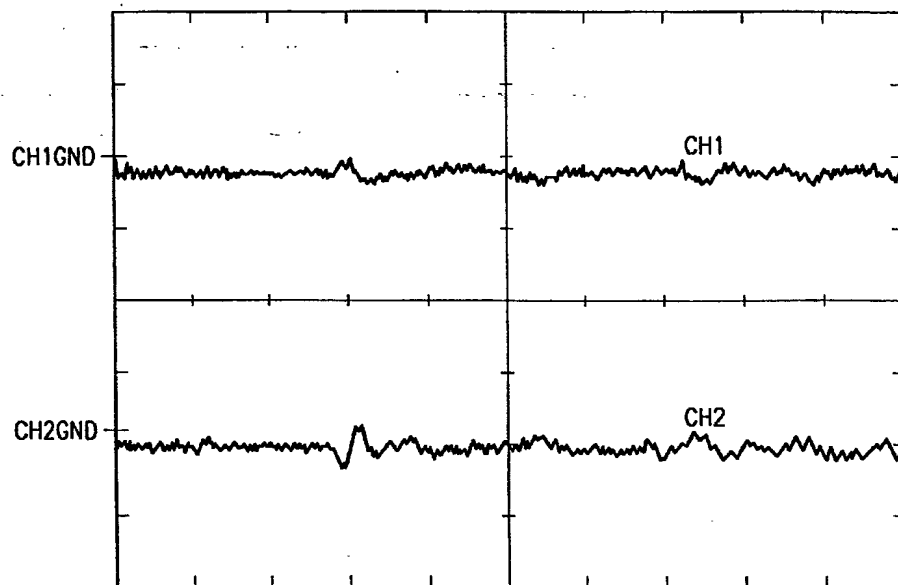
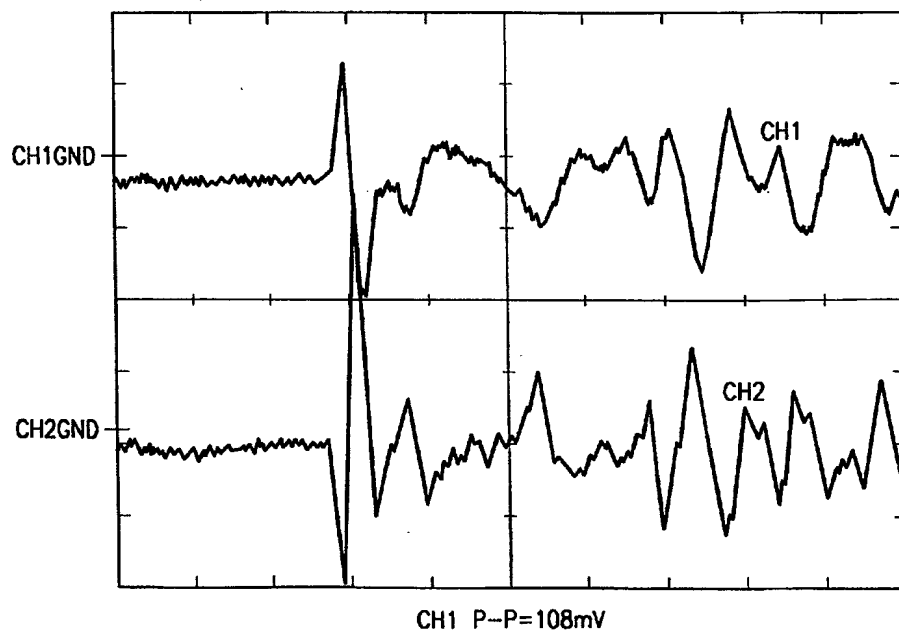


FIG. 7



INTERNATIONAL SEARCH REPORT

International application No.
PCT/US99/14659

A. CLASSIFICATION OF SUBJECT MATTER

IPC(6) :G01B 09/02
US CL :356/345

According to International Patent Classification (IPC) or to both national classification and IPC

B. FIELDS SEARCHED

Minimum documentation searched (classification system followed by classification symbols)

U.S. : 356/345, 432

Documentation searched other than minimum documentation to the extent that such documents are included in the fields searched
none

Electronic data base consulted during the international search (name of data base and, where practicable, search terms used)

US PTO APS: ultrasonic, pulsed beam, phase modulation

C. DOCUMENTS CONSIDERED TO BE RELEVANT

Category*	Citation of document, with indication, where appropriate, of the relevant passages	Relevant to claim No.
A	US 5,619,326 A (TAKAMATSU et al) 08 April 1997 (08.04.1997), see entire document	1-20

☐ Further documents are listed in the continuation of Box C. ☐ See patent family annex.

* Special categories of cited documents:	"T" later document published after the international filing date or priority date and not in conflict with the application but cited to understand the principle or theory underlying the invention
"A" document defining the general state of the art which is not considered to be of particular relevance	"X" document of particular relevance; the claimed invention cannot be considered novel or cannot be considered to involve an inventive step when the document is taken alone
"E" earlier document published on or after the international filing date	"Y" document of particular relevance; the claimed invention cannot be considered to involve an inventive step when the document is combined with one or more other such documents, such combination being obvious to a person skilled in the art
"L" document which may throw doubts on priority claim(s) or which is cited to establish the publication date of another citation or other special reason (as specified)	"A" document member of the same patent family
"O" document referring to an oral disclosure, use, exhibition or other means	
"P" document published prior to the international filing date but later than the priority date claimed	

Date of the actual completion of the international search

16 AUGUST 1999

Date of mailing of the international search report

03 SEP 1999

Name and mailing address of the ISA/US
Commissioner of Patents and Trademarks
Box PCT
Washington, D.C. 20231

Facsimile No. (703) 305-3230

Authorized officer

ROBERT KIM

Telephone No. (703) 308-0916